Ring Resonator Measurement: Characterizing High Dielectric Constant Materials for the Fourth Industrial Revolution

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Abstract: This study introduces a ring resonator measurement technique targeting high dielectric constant materials. Operating within a frequency range of 0.1 GHz to 5 GHz, the resonator utilizes FR4 substrate and copper conductor. A significant departure from existing methods involves employing a silver-coated ring directly on the sample, mitigating Wheeler’s gap issue induced by airgaps across material layers. Furthermore, the research reveals that as dielectric constants increase, microstrip line impedance drastically falls below 25 ohms, potentially leading to inaccurate loss tangent determinations. This paper focuses solely on HFSS simulations to demonstrate the method’s feasibility. The proposed technique offers promising prospects for accurately characterizing high dielectric constant materials, thereby facilitating advancements in various applications, particularly within the Fourth Industrial Revolution framework- 5G and 6G technologies.

Keywords: Electromagnetics; Dielectric Measurement; Ring Resonator, RF, MLCC

Introduction

Multilayer Ceramic Capacitors (MLCCs) play a crucial role in contemporary electronics, thanks to their high capacitance values and compact design. Among the materials commonly employed in their construction, Barium Titanate (BTO) stands out for its exceptional dielectric properties, their dielectric constant values can go as high as 4,000 and low dielectric loss [1, 2]. However, accurately characterizing BTO-based MLCCs presents significant challenges due to their high dielectric constants and multilayered structures [3]. This becomes specifically challenging, compounded by the fact that the dielectric material properties vary according to the frequency regime. Figure 1 shows the measurement techniques and frequency regimes.

Existing measurement techniques often struggle to provide precise evaluations of such high dielectric constant materials, resulting in inaccuracies in device performance predictions and impeding further technological advancements.
To address these limitations, this article presents a modification of the existing ring resonator method tailored specifically for the precise characterization of high dielectric constant materials, with a particular focus on MLCCs. By refining the conventional approach, this modified technique holds the potential to significantly improve the assessment and optimization of MLCC performance, thereby advancing various electronic applications.
Figure 2. Issues with Parallel Plate Measurement method uses Agilent Dielectric Material Test Fixture (16453A). The measurement of high dielectric constant materials leads to resonant peaking beyond 800MHz.

Related work
Use of ring resonators in the not a new technique and has been in use for quite a few decades now[3]. Heinola & Tolsa in 2006 demonstrated the use of ring resonators for the purpose of dielectric measurements [4]. Their work explores the adaptation of theoretical models of ring resonator structures to calculate the relative permittivity of low-loss and high-loss printed wiring board materials across a frequency range from 250 MHz to 10.0 GHz. Additionally, it reviews the characterization of the loss tangent using the ring resonator method, highlighting variations in results due to different approximations for conductor losses of the microstrip line. The study is grounded in experimental research involving various microstrip and strip line ring resonator structures. The findings offer valuable insights into the application of the ring resonator technique for accurately measuring the relative permittivity and loss tangent of dielectric substrates, thus enhancing the understanding of material properties crucial for printed wiring board applications. The resonant frequencies of the microstrip ring resonator may be estimated using the subsequent equation [4]:

\[ 2\pi R = n\lambda_g \]

Here where \( r \) is the radius (mean) of the ring and \( n\lambda_g \) is a wavelength or a harmonic of the wavelength.
Key Contribution
In this research we have introduced a method to coat the Material Under Test (MUT) to avoid airgap issues that hamper the high dielectric measurement (refer Figure 3).

- Usually the MUT is the substrate itself.
- However as the MUT dielectric constant is high, it becomes increasingly difficult to maintain the Characteristic impedance at 50 ohms

Figure 3. Ring Resonator construction.
Presence of Airgaps

Figure 4.a shows the widely used setup known as material under test (MUT) on top. $Z_0$ is maintained at 50 Ω. Material Under Test (MUT) directly placed on the ring and the corresponding changes in properties can characterize the dielectric and loss tangent properties. However, accurate calculation techniques must be applied at the $\epsilon$ increases beyond 10.

Incorporating MUT directly atop the ring resonator introduces a challenge due to the air gap between the MUT and the ring, leading to a shift in the resonance peak (As shown in Figure 4b). This issue has long plagued existing measurement setups employing MUT on top configurations. To mitigate this effect, metallizing the MUT with dimensions matching those of the ring structure of the ring resonator helps preserve the resonant properties. Additionally, addressing the multilayer dielectric layer problem necessitates transforming it into a multi-layer problem, wherein Wheeler’s and Schneider’s filling factors
of microstrip line theory become essential. By considering these factors, researchers can effectively tackle the complexities arising from the interaction between the MUT and the ring resonator, ultimately enhancing the accuracy and reliability of measurements in such setups.

Method, Experiments, Results and Discussions

**Modification in the MUT to remove Airgaps**

![Diagram of the MUT structure](image)

The proposed method followed in this paper is shown in the figure 5. The MUT is coated with silver paste through a process very similar to the popularly known technique known as metallization which is also described in Agilent’s dielectric measurement manuals for sample preparation. The case shown in figure 5 can be converted into a problem of 3 layers as shown in figure 6, where the MUT is the top layer, the copper or metal of the transmission line and ring and the last layer is the FR4 substrate. The 3-layer structure undergoes a process of conformal mapping, wherein the boundaries are initially assumed to extend to infinity in the complex plane and are subsequently transformed into cyclic closed loop forms. This angle-preserving technique facilitates mathematical calculations by simplifying the representation of the structure. The purpose of this mapping is to ascertain the degree of filling of dielectric layers within a microstrip line, allowing for a comprehensive understanding of the distribution and behavior of electromagnetic fields within the system. By employing conformal mapping, researchers can effectively analyze and optimize the performance of microstrip lines, leading to advancements in various applications ranging from telecommunications to microwave engineering.

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https://www.spast.org/ojspath
Figure 6. The Wheeler-Schneider filling facto method for transmission line on a dielectric slab and an MUT on top.

**Multilayer resonator Dielectric constant determination**

The resonant frequency for an unloaded resonator is given by $f_{r1}$, likewise for a loaded one the shift in resonance is given by $f_{r2}$ (3,4)

(Eq 2)

$$\varepsilon_{eff,2} = \left( n \cdot \frac{f_{r1}}{f_{r2}} \right) \varepsilon_{eff,1}$$

Where $n=1,2,3$...

Relative permittivity for multilayer can be found by using filling factors defined in previous slides (3,4):

(Eq 3)

$$\varepsilon_{r,2} = \psi(f) \frac{q_2(\varepsilon_{efr} - q_1\varepsilon_{r,1})}{(1-q_1)^2 - (1-q_1-q_2)(\varepsilon_{efr} - q_1\varepsilon_{r,1})}$$

Where $\psi(f)$ is the correction factor which is a Resonant Frequency dependent quantity. The Q-factor is changed when dielectric slab is introduced. The relationship is given by (3,4):

(Eq 4)

$$\frac{1}{Q_{D,2}} - \frac{1}{Q_{D,1}} = \frac{1}{Q_{U,2}} - \frac{1}{Q_{U,1}}$$

Where U implies unloaded resonator, whereas D represents dielectric slab loading. Furthermore:

(Eq 5)

$$\sum_{i=1}^{N} p_{1,N} \tan \delta_i = \frac{1}{Q_{D,N}}, \quad \tan \delta_2 = \frac{1}{p_{2,2}} \left( \frac{1}{Q_{D,2}} - \frac{1}{Q_{D,1}} \right) + \frac{p_{1,1} - p_{1,2}}{p_{2,2}} \tan \delta_1$$
Where $p_{2,2}$, $p_{1,1}$, and $p_{1,2}$ are Schneider filling factors that are in-turn related to Wheeler filling factors (Eq 6)

$$p_{1,2} = \frac{\varepsilon_{r,1}}{\varepsilon_{eff,2}} q_1$$

$$p_{2,2} = \frac{\varepsilon_{r,2}}{\varepsilon_{eff,2}} q_2 \left(1 - q_1\right)^2 \left(\varepsilon_{r,2} (1 - q_1 - q_2) + q_2 \right)^2$$

*Resonance peaks as a function of Dielectric constant*

![Figure 7](https://www.spast.org/ojspath)

**Figure 7. Resonance Peaks as a function of dielectric constant**

The resonance peak for $n=1$ is at 1.08 GHz for the resonator whereas the peak shift for $\varepsilon_r$=400; 500; 600 and 700.

![Figure 8](https://www.spast.org/ojspath)

**Figure 8. Dielectric constant and loss tangent estimated from Wheelers VS expected from HFSS**
The figure 8 shows the plot for the dielectric constant as a function of frequency.

**Conclusions**

1. **Introduction of a Modified Ring Resonator Technique:** Our research endeavors to introduce a novel approach to ring resonator measurements, specifically tailored to address the challenges associated with characterizing high dielectric constant materials, notably Multilayer Ceramic Capacitors (MLCCs). These materials, exemplified by Barium Titanate (BTO), pose significant hurdles due to their complex, multilayered structures and frequency-dependent properties.

2. **Mitigation of Measurement Challenges:** Conventional measurement techniques often encounter difficulties in accurately assessing high dielectric constant materials due to air gaps and variations in dielectric properties across different frequency ranges. To circumvent these challenges, our proposed technique involves directly coating the sample with silver paste, thereby reducing the impact of air gaps and ensuring more precise measurements.

3. **Enhanced Accuracy through Advanced Methodologies:** Leveraging conformal mapping techniques and incorporating Wheeler’s and Schneider’s filling factors, our methodology aims to improve the accuracy and reliability of dielectric property characterization. By comprehensively analyzing the electromagnetic field distribution within the system, we seek to provide deeper insights into the behavior of high dielectric constant materials.

4. **Experimental Validation and Insightful Findings:** Through a combination of experimental validation and simulation using HFSS, our study demonstrates the efficacy of the proposed technique in estimating dielectric constants and loss tangents. We present compelling evidence of resonance peak shifts with increasing dielectric constants, underscoring the importance of our approach in accurately characterizing multilayer dielectric structures.

5. **Implications for Future Technological Advancements:** The implications of our research extend beyond mere methodological advancements. By facilitating more accurate characterization of high dielectric constant materials, particularly in the context of emerging technologies like 5G and 6G, our work lays the foundation for significant advancements in electronic applications. Our findings hold promise for driving innovation and optimization in various sectors within the framework of the Fourth Industrial Revolution.

**References**


